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**FABRICATION OF COMPOSITE HIGH TEMPERATURE
SUPERCONDUCTOR WIRES FROM $\text{Ag/YBa}_2\text{Cu}_3\text{O}_x$
POWDER PRODUCED BY AgNO_3 DECOMPOSITION**

BY WILLIAM A. FERRANDO

RESEARCH AND TECHNOLOGY DEPARTMENT

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FOREWORD

The recent discovery of a family of metal oxide ceramic materials which display superconductivity at liquid nitrogen temperature and above has stirred the imagination of many in both the technical and consumer sectors. Numerous applications, heretofore too costly using conventional low temperature superconductors, may become practical with the new materials.

The Navy, in particular, has recognized the possibilities in electric motor fabrication, wave guides, low noise electronics among others and has maintained support for research in this area.

These high temperature superconductor (HTS) materials will emerge from being simply laboratory curiosities to the real world of new devices only when they can be fabricated in useful forms. Since the base materials are synthesized as refractory particulate ceramics, practical techniques must be developed to produce thin films and flexible wires which maintain the high superconducting transition temperature T_c and current carrying capacity J_c of the individual particles themselves. This report describes a technique developed at the Naval Surface Warfare Center (NSWC) for modifying the base material to make possible the fabrication of wires and films which retain the desirable superconducting properties.

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CHAPTER 1

INTRODUCTION

For the first 75 years since the discovery of superconductivity by Kamerling-Ohnes in 1911, it had been limited to below about 24 K. This situation changed dramatically in the fall of 1986 when researchers at several laboratories^{1,2} reported evidence of superconductivity at temperatures significantly higher than hitherto had been considered possible. Moreover, the phenomenon was observed to occur in a family of metal oxide ceramic materials (which recently have been shown to have some metallic band structure³ but) which are normally semiconducting at best. The dramatic increase in superconducting transition temperature (T_c) is shown in Figure 1. The high temperature limit is about 125 K for some of these ceramics at present. The implications of this discovery and subsequent development are that practical devices eventually can be made which operate at liquid nitrogen temperature (77 K). This will simplify system refrigeration requirements/costs and should significantly expand the applications horizon.

As is the case with many basic discoveries, the challenge becomes moving some from the realm of laboratory curiosity to use in practical applications. In the case of high temperature superconductivity (HTS), ready applications are not wanting. A sustained imaginative developmental effort, however, will be required to produce these materials in fabricable form with consistent properties.

CHAPTER 2

BACKGROUND

The state of superconductivity, which has been widely observed in pure metals and alloys, displays the unique physical properties of finite temperature zero resistance and magnetic flux exclusion. The curves resistance versus absolute temperature (Figure 2) compare the behavior of a normal conductor and a superconductor. The normal conductor resistance (A) decreases in a roughly linear manner as its temperature is reduced. The resistance of the superconductor (B), by contrast, decreases abruptly at a finite temperature (T_c) to a vanishingly small value. At this point, a current passing through the wire will do so with no heat dissipating losses. If a sufficiently large current can be carried and durability and stability conditions can be met, the film or wire becomes useful for various device applications. Figure 3 illustrates the magnetic flux exclusion brought about by the perfect diamagnetism of the superconducting state. A magnetic field is applied to the superconductor in its normal state with $T > T_c$ (left). The field penetrates the superconductor. As its temperature is reduced to $T < T_c$ (right), the magnetic flux is excluded. The impinging field induces currents near the superconductor surface which screen the external field and prevent it from penetrating. If a small strong magnet is placed above the superconductor, the former will be observed to float upon its rejected field. This levitation is known as the Meissner Effect.⁴ The properties we have discussed are of more than passing interest. They form the basis of the potential utility of these materials from levitating trains and bearings to superconducting motors, computers and electric transmission systems.

The now famous Bardeen, Cooper, Schrieffer (BCS) theory⁵ sets forth a cooperative mechanism of the electrons with the atomic lattice which offers an explanation of the indirect attraction of electron pairs which proceed unimpeded through the conventional metal superconductors. While several analogous interactions have been proposed⁶ for the new ceramic superconductors, the exact mechanism is as yet not known.

THE CHALLENGE

These HTS ceramics, by nature, are brittle. Therefore, they cannot withstand any significant tensile stress, they are difficult to join, and they are prone to cracking by thermal shock or expansion mismatch with substrates, especially when they must be cycled to low temperatures. They are difficult to form into arbitrary shapes, especially those such as wire which must have sufficient flexibility for further processing. The HTS materials, moreover, require rather long and careful annealing schedules to achieve proper oxygen stoichiometry for optimal superconducting prop-

erties. They are unstable upon sustained exposure to atmospheric moisture, or even to oxygen loss when exposed to vacuum, so that environmental protection must be provided. They are attacked by most metals during high temperature processing and react with many vessel materials during synthesis.

The family of high temperature superconductors includes such compounds as $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ ($T_c = 90 \text{ K}$), $\text{Bi}_{1.7}\text{Pb}_{0.3}\text{SrCaCu}_{1.8}\text{O}_x$ ($T_c = 110 \text{ K}$) and $\text{Tl}_2\text{Ba}_2\text{Ca}_2\text{Cu}_3\text{O}_{7-x}$ ($T_c = 118 \text{ K}$). Although critical temperatures (T_c) approaching ambient would be quite desirable, increase of this parameter is far from the whole story with the new superconductors. In general, a superconductor must have practical ranges of temperature, current density, and applied magnetic field in which they operate. Recent research with the new materials indicates that this condition may be difficult to achieve outside of single crystals.

This further complication with the ceramic superconductors involves their so-called "weak link superconductivity problem." Apparently, the correlation of the superconducting wave functions is considerably weakened upon crossing the boundaries between adjacent grains. The grain boundaries act as walls which are relatively weakly transparent to the wave functions. In the case of the conventional low temperature superconductors, the regular array of metallic atoms in the superconducting alloys allows the wave functions to correlate virtually unimpeded over sample dimensions. Lattice dislocations introduced in the wire fabrication process do not produce severe disruption of the wave functions in their relatively isotropic lattices. The dislocations are, however, useful in stopping or pinning magnetic flux inclusions present within the wire in the superconducting state. They are thus prevented from movement which causes energy to be absorbed and resistance to appear.

Since most potential applications require operation with large current densities and magnetic fields (either self induced or externally applied), some means of greatly increasing the intergrain wave function correlation in the HTS ceramics must be found. This may be a more difficult task than any encountered thus far in fabrication.

CHAPTER 3

SILVER COATING BY AgNO_3 DECOMPOSITION

RATIONALE FOR SILVER ADDITION

It would be desirable if some material addition could be found which is capable of closely bonding the ceramic superconducting particles by appropriate processing, while allowing the supercurrents to pass essentially undiminished. It has been found that silver and gold have these characteristics. While gold is generally too expensive for consideration, the use of moderate amounts of silver in fabrication should be acceptable.

The first question logically is "Why silver?" There are several important factors which favor such addition based upon the properties of the ceramic superconductor compounds:

1. The presence of silver greatly improves the normal state conductivity. This will be important in devices if a superconducting component accidentally goes normal during operation. The low normal state resistance means less excess joule heat must be dissipated.
2. The silver will improve the ductility of the superconductor material, allowing various wire fabrication methods to be pursued.
3. Silver can provide intimate interfacial bonding of the superconductor particles which will be necessary for high critical current carrying capacity (J_c).
4. The presence of silver at particle interfaces increases the crossover distance of the superconducting wave functions. In vacuum, only a 15 Å ($1 \text{ Å} = 10^{-8} \text{ cm}$) gap can be bridged by these wave functions, making even tiny cracks obstacles to superconducting continuity. Silver should facilitate attaining fully dense material by the available forming methods.
5. Finally, silver coating may provide the required long-term environmental protection necessary for viability in most device applications.

SILVER ADDITION BY CONVENTIONAL METHODS

For superconductor applications, there are difficulties with conventional methods of silver addition.

1. Mixing of powders, however fine, does not achieve uniformity of silver coverage at the scale of HTS particle dimensions. To be sure, because of its high

ductility, the silver will be considerably smeared throughout the material by the rigors of forming, although true microscopic homogenization is not achieved.

2. Electro or electroless plating of silver onto the HTS particles is possible, but quite difficult in practice. A major obstacle here, however, is the aqueous electrolyte which is deleterious to the HTS material.

3. Chemical vapor deposition (CVD), plasma spray, or sputtering could be used, but again these methods are difficult to apply to powders. In addition, exposure of HTS materials to vacuum environment results in loss of oxygen stoichiometry with consequent deterioration of superconducting properties.⁷

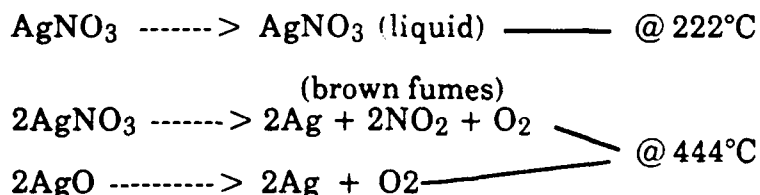
4. Finally, coating by simply mixing in liquid silver at high temperature would be difficult at the low silver fractions which are required. The high temperature at which this must be done would pose problems of contaminants, oxygen loss and decomposition of the HTS material. Therefore, no conventional method of introduction of silver into HTS materials has been completely satisfactory.

THE AgNO₃ DECOMPOSITION METHOD

The rather stringent requirements on silver addition to HTS materials have generated an entirely new approach. The reasoning was that if a compound could be found which decomposes at moderate temperature leaving behind only silver, this could be used to coat the HTS particles. If it did not otherwise chemically react with the superconductor, the process should provide good candidate starting material for various bulk forming procedures, such as swaging, extrusion, and rolling, or even as a base for HTS paints and films.

Virtually all metals and compounds are subject to oxidation of one form or other when they are heated in air. The exception are the noble metals, notably silver and gold. These revert to their unoxidized state and separate from any dross upon application of high temperature. Chemical compounds of Au and Ag behave likewise.

In particular, AgNO₃ (silver nitrate) is found to behave upon heating roughly as follows:



The liquid phase is found to be very low in viscosity and highly wetting to virtually any material, especially to ceramics. At decomposition, a highly pure film of active atomic silver remains. The decomposition temperature is sufficiently low that most metal surfaces to which the AgNO₃ is applied do not oxidize significantly. Of particular importance for the HTS application is the absence of reactivity of AgNO₃ with the superconductor particles during the coating process.

QUALITY CONTROL/COATING UNIFORMITY

A high degree of homogeneity of silver distribution in a batch of coated HTS powder is easily achieved if the method is correctly applied. A quantity of AgNO_3 scaled by the atomic fraction of Ag is mixed into the HTS material required to yield the desired weight percent of silver in the final product after decomposition.

High Silver Concentration (> 15 wt%)

In this range, the AgNO_3 may be ground and mixed directly with the HTS powder. Upon heating above 222°C , sufficient liquid AgNO_3 is present to wet the powder particles uniformly with hand or machine stirring. As the temperature is raised further toward decomposition, the liquid becomes very fluid, ensuring an even more thorough coverage of the powder.

Low Silver Concentration (< 15 wt %)

In this region, the quantity of AgNO_3 liquid is generally inadequate to assure uniform coverage due to its finite wetting ability. This problem is quite easily solved, however. The appropriate quantity of AgNO_3 is first dissolved in a nonaqueous, inert liquid such as ethylene glycol (solubility: $\sim 7.5\text{g AgNO}_3/10\text{ ml glycol}$). The measured amount of HTS powder is mixed into this solution. The glycol carrier then is evaporated at somewhat elevated temperature ($50\text{--}80^\circ\text{C}$). Too high an evaporation temperature was found sometimes to cause ignition of the mixture and high temperature combustion. This may leave undesirable products behind in the Ag coated HTS powder, but, more importantly, fuses portions of the ceramic and melts the Ag off the powder particles into separate globules. After this preparation, the material is treated as above. As a means of possibly improving the uniformity of silver deposition in the product material, the mass may be stirred during the AgNO_3 melting and decomposition steps.

MORPHOLOGY OF THE Ag COATED POWDERS

Figure 4 shows a set of x-ray diffraction spectra on coated 123 HTS powder samples coated with silver by the AgNO_3 process. The samples were processed for approximately 2, 8, and 15 wt% Ag, respectively. The spectra show a proportionate increase of the indicated Ag peak from the 2 wt% sample (bottom) to the 15 wt% sample (top). The relative intensity of the Ag peaks indicate that the intended Ag content is present in the final product. Such x-ray spectra also can be used to detect both impurities in the HTS starting material and for reaction products of the coating process. The 15 w/o spectrum, in fact, shows a small amount of carbonate which was eliminated in subsequent sintering.

A scanning electron microscopy (SEM) picture shows the degree of Ag coating uniformity achieved by this method on a microscopic scale. Figure 5 (left) shows a 123 HTS particle in its as-received state. Its apparently sintered microparticulate surface structure contains numerous tiny cavities. A similar particle is shown after coating (right). The surface cavities have been largely filled and the particle appears considerably smoother. By inference, this confirms the degree of Ag distribution on the microscopic scale. Individual particles also can be scanned for constituent metallic elements via the associated EDAX scanning system. This will be carried out and reported at a later date.

CONDITIONS FOR PRODUCTION OF FINE WIRES

Production of flexible continuous fine wires by any one of the wire-making methods described below will be a great challenge with high temperature superconductor materials. The small brittle particles must be somehow coaxed into a fiber-like morphology. While materials inherently more brittle such as glass and, more recently, SiC have been formed into strong filaments, it is apparent that ingenuity and finesse of processing will be required in the present case. Fiber spinning techniques such as have been developed for glass and alumina are not directly applicable because of poor melt properties of the HTS materials. The addition of silver certainly will aid in interparticle bonding and in improved ductility, but other factors will be important. Production of an interleaving platelet microstructure along the fiber axis with appropriate heat treatment may be critical, especially in achieving high current carrying capability. Uniformly sized particles much less than the intended fiber diameter might be required as starting material. On the other hand, smaller particles mean more contact surfaces on a microscopic scale to be sintered. This may aggravate the weak link superconductivity problem. Thus it is fair to say that there are still many unanswered questions.

CHAPTER 4

WIRE FABRICATION TECHNIQUES

The wire fabrication techniques of swaging, extrusion, and drawing have been well developed in industry practice over many years. These methods have the advantages of relatively low cost and wide applicability. Machines have been designed to produce the product quickly and efficiently. Most commercial wires are fabricated by an appropriate combination of the above. All that is required of the starting material is sufficient ductility, heat treatability, and stability in air for processing. As one might expect, certain originality in approach must be used in applying these techniques to other than conventional metals.

SWAGING

Swaging is accomplished using a machine fitted with a radial hammer assembly. A rod or billet is axially inserted and is hammered down to smaller diameter. The operation is repeated with progressively smaller orifices. A swaging machine is shown in Figure 6. The HTS ceramic particles, in particular, must be packed in an appropriate ductile tube prior to swaging. Such a filled tube before swaging is shown in Figure 7 (lower) and afterward in a coiled shape (upper). The ratio of pre- to post-swaging diameter is typically about 4:1, although this is limited, in principal, only by the dies available. The core HTS material is pressed to virtual 100 percent density in the process, eliminating voids which might be produced by other methods.

The thin remaining metal jacket ultimately will be valuable for protection against environmental degradation and mechanical damage. In the development stage, however, the presence of the jacket has proven to be somewhat of an obstacle for testing and further processing. The tubing material of choice, viz, silver, has a very low inherent normal resistivity which necessitates sensitive instrumental scales for (T_c) and relatively high currents for J_c measurements. Of perhaps greater significance, the post-swaging 900°C oxygenation treatment which has been found necessary to produce optimal superconducting characteristics. Apparently, the large compacting forces of swaging cause some oxygen depletion or dislocation at the HTS particle interfaces which must be restored by oxygenating heat treatment. This can be performed with the jacket only if it is very thin. Fortunately, a method has been found to remove the jacket from segments of the swaged product for testing and further treatment.

EXTRUSION

Wire also can be produced by extrusion. This is accomplished by forcing a charge of material (billet) through a die much in the same manner as spaghetti is

made. Figure 8 shows an extrusion die and small billet (pressed from the 123 powder coated by the AgNO_3 process in the present application). If the material is sufficiently ductile, it may be extruded directly. The heater may be activated to perform the extrusion at elevated temperature. If the material is brittle, as is the case with the HTS ceramics, a binder or polymer carrier may be added to facilitate the extrusion. This is burned away in subsequent processing. Several advantages of this method in HTS processing include the absence of the restricting metal jacket and good flexibility before final heat treatment. A protective coating may be added later. The flexibility will allow coils to be wound and heat treated in situ for some device applications.

DRAWING

The name is descriptive of this method. The starting rod is drawn or pulled through successively smaller conically convergent dies. Drawing can be employed in conjunction with swaging to achieve smaller wire diameter. An additional constraint of drawing not present in swaging, however, is the requirement of sufficient tensile strength at each pass through the die.

CHAPTER 5

WIRE FABRICATION AND MEASUREMENT OF PROPERTIES

Many early attempts were made at fabricating superconducting buttons and wires, principally by swaging. Buttons of 123/Ag composite powder were made by compaction in a die using a punch press. Meissner levitation was observed in samples up to about 25 wt% Ag. This demonstrated the passage of supercurrents through the silver coating on the particles. It also showed the approximate allowable limit of silver in composite wires for retention of superconductive properties.

Swaged "wires" were fabricated using commercial HTS 123 material (Grace Specialty Chemicals, Davison Chemical Division, Dept. TR, P. O. Box 2117, Baltimore, MD 21203) in an uncoated state and after coating with Ag (generally 15 wt%) using the AgNO_3 process. The powders were tamped into copper tubes which were sealed at their lower ends. After sealing their tops, the tubes were swaged. Figure 9 shows a processing flow chart detailing various routes of wire fabrication. Due to work-hardening, it was necessary to anneal the copper tube after several passes to restore ductility. It was found,⁸ however, that exposure to such temperatures causes the copper to extract oxygen from the 123 compound within the tube, forming CuO at the interface. This essentially destroys the structure of the superconductor and its useful properties.

Silver tubes were employed in all subsequent swaging. Silver has several advantages. It does not work-harden and can be extensively swaged, if desired. Moreover, its noble character preserves it from oxidation at elevated temperatures, so that it does not tend to capture oxygen from the superconducting core.

CRITICAL TEMPERATURE (T_c) MEASUREMENT

Figure 10 is a block diagram of the apparatus used in the T_c measurements. The milliohmmeter is a Keithley Model 503. To obtain the resistance versus temperature in practice, the segment of wire is lowered very slowly into the dewar. Readings from the dual pen recorder allow the sample resistance versus temperature to be plotted.

Pellet samples were fabricated at first by direct compaction of the Ag coated 123 powder in a die to about 5000 psi. The intent was to check the 123 starting material, Ag coating process, and optimal Ag fraction prior to actual wire fabrication. After sintering for 15 hours at 900°C in O_2 , pellets containing up to about 30 wt% Ag exhibited a Meissner Effect at 77 K. Figure 11 shows the resistance versus temperature dependence of a pressed Ag/123 composite HTS pellet. It shows a rather sharp superconducting transition (< 10 degree width) having onset at about 90 K.

Swaged wires were produced following the procedures outlined above. The final annealing or "oxygenation," however, required removal of the Ag jacket to allow sufficient oxygen penetration. This was accomplished for short segments of the 0.155-inch diameter wire by grinding and peeling. Figure 12 shows an optical microstructure of a portion of rod formed by decomposing AgNO_3 mixed with particles of 123 superconductor. The Ag (bright regions) appears intermingled with even the smallest particle. Figure 13 shows a typical micrograph cross section of the 123/Ag swaged wire. The high degree of Ag distribution uniformity is shown in the bottom picture. Figure 14 shows the four contact test mounting of such a wire segment after a 15 hour anneal at 900°C in O_2 . The leads have been attached with an Ag paste.

Figure 15 (left side) shows the variation of resistance with temperature (K) of a typical swaged and annealed wire of 123/Ag powder produced by AgNO_3 decomposition. The relatively sharp superconducting transition temperature has its onset at about 90 K for these wires. The result of a magnetic moment measurement is indicated in Figure 15 (right side). The linear portion of the curve above 90 K indicates complete magnetic flux penetration of the 10 Oe field through the wire segment. Below 90 K, the superconductor begins to assume a diamagnetic (negative) moment as the magnetic field is progressively excluded. At low temperature, with complete exclusion, the moment becomes constant.

MEASUREMENT OF THE CRITICAL CURRENT (J_c)

Measurements of the current carrying capacity of the wires have been made. The apparatus constructed for these measurements is shown in Figure 16. The microvoltmeter used was a Hewlett Packard Model 425A, having a sensitivity of 10 microvolts full scale. With pen recorder amplification, 1 microvolt was readily detectable. A dc power supply of appropriate current range was employed, depending upon the diameter of wire to be tested. The potential leads (see figure) were placed at least 1 cm apart on the wire samples. Since the criterion for a superconducting wire segment has been set at 1 microvolt/cm or less, the described experimental setup is quite adequate for the present J_c measurements.

Figure 17 shows applied dc current density (in 0 applied magnetic field) versus potential across the sample for a 0.155-inch (0.394 cm) diameter swaged and annealed wire segment at 77 K. The critical current J_c for this sample is about 125 Amps/cm². The sample was thermal cycled several times to 77 K during subsequent testing. It then was stored for several months in the lab ambient with no special precautions. Retesting the wire yielded an unchanged J_c value.

These results are very interesting in light of the marked tendency of the HTS 123 materials to deteriorate, both with thermal cycling and with exposure to moisture. Apparently the silver addition in the strongly adherent and microscopically uniform manner of the AgNO_3 decomposition process introduces a great measure of stability to the wires. The deposited Ag accomplishes this in at least two ways. First, it provides protection against the effects of environmental moisture. Second, the coefficients of thermal expansion are very nearly equal for Ag and HTS 123. This feature should aid in inhibiting the microcracking which has been observed to degrade these materials in use. Optimization of the wire fabrication techniques for

the HTS materials is yet to be done. Improvement in the important HTS wire properties, especially in J_c are anticipated as experience is gained and the various wire forming techniques are fully exploited utilizing the new HTS/Ag composite powder materials.

CHAPTER 6

SUMMARY

The new families of high temperature superconducting ceramics hold great promise for broad device applications, but only if they can be fabricated with consistent and durable properties in useful form. The nature of these HTS materials is making the realization of this promise a most formidable challenge.

Many applications will require the high temperature superconductors to be produced in wire form. In order to provide sufficient ductility, environmental protection, and stability to thermal cycling, addition of an appropriate metal to the HTS material will most likely be necessary. Only the noble metals, however, appear to have the degree of compatibility required. Silver alone stands as the additive metal of choice, as having the proper combination of physical properties.

Beneficial effects of silver addition already have been shown in work utilizing fine powders of Ag or AgO. The problem has been to produce a uniform microscopic coating of silver on the HTS materials by nonaqueous means at relatively low temperature and reasonable cost. Such a method has been developed using AgNO₃ decomposition. Wires have been fabricated by adaptation of standard methods using composite HTS 123/Ag powders exhibiting superconducting transition temperatures (T_c) of ~90 K and critical currents (J_c) of 100-200 Amps/cm². The prospect for improved wire product with refinement of the coating technique and optimization of processing parameters appears to be good.

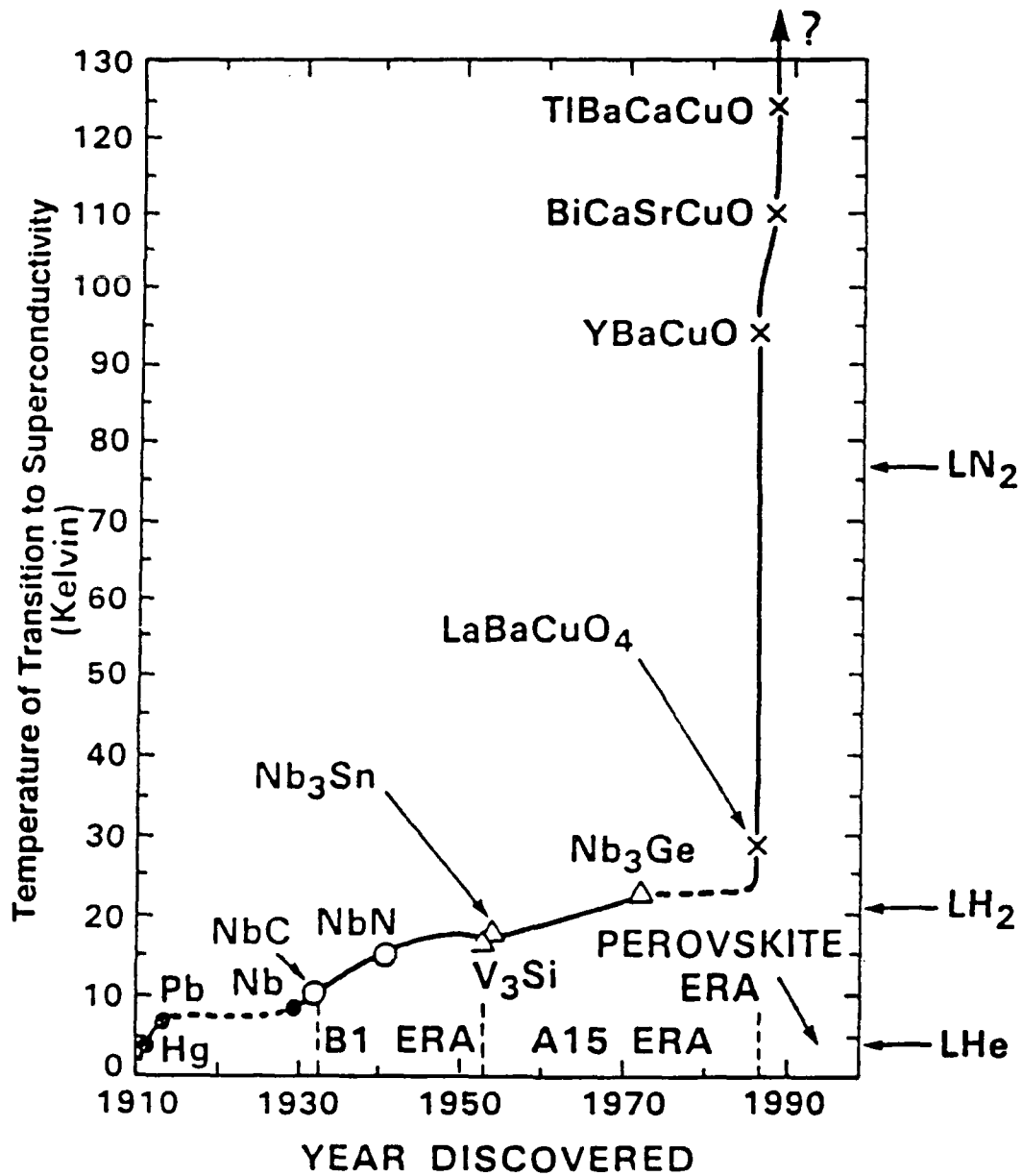


FIGURE 1. TIME LINE FOR DISCOVERY OF SUPERCONDUCTORS

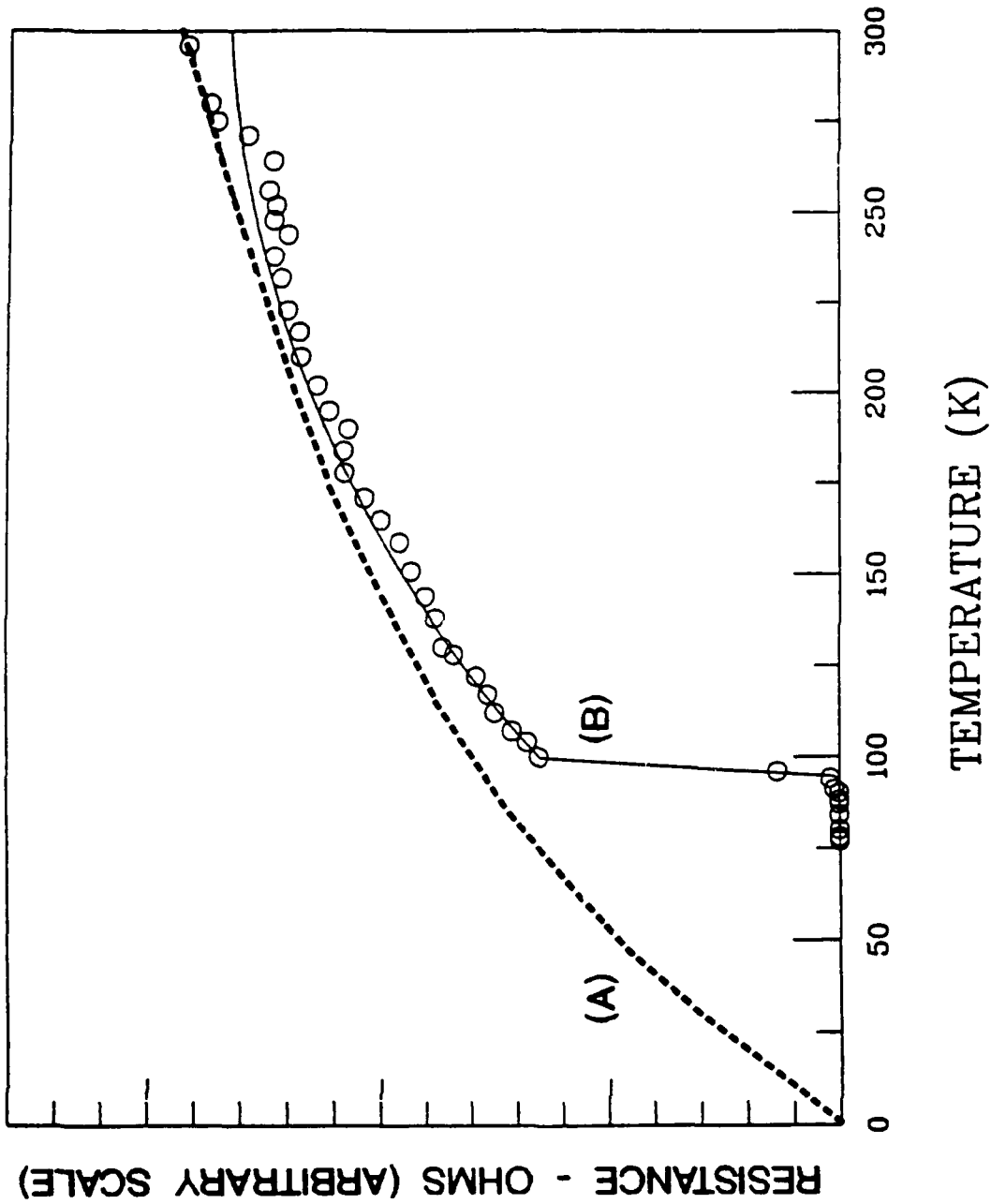


FIGURE 2. VARIATION OF RESISTANCE WITH DECREASING TEMPERATURE

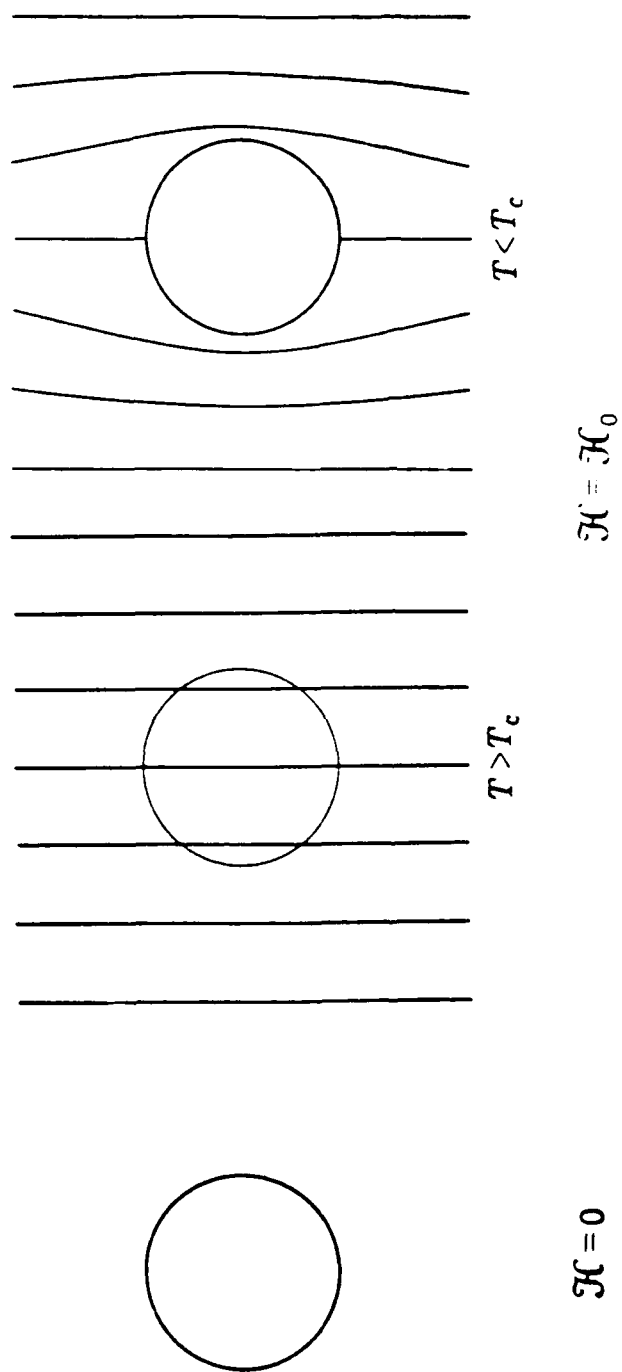


FIGURE 3. ILLUSTRATION OF THE MEISSNER EFFECT

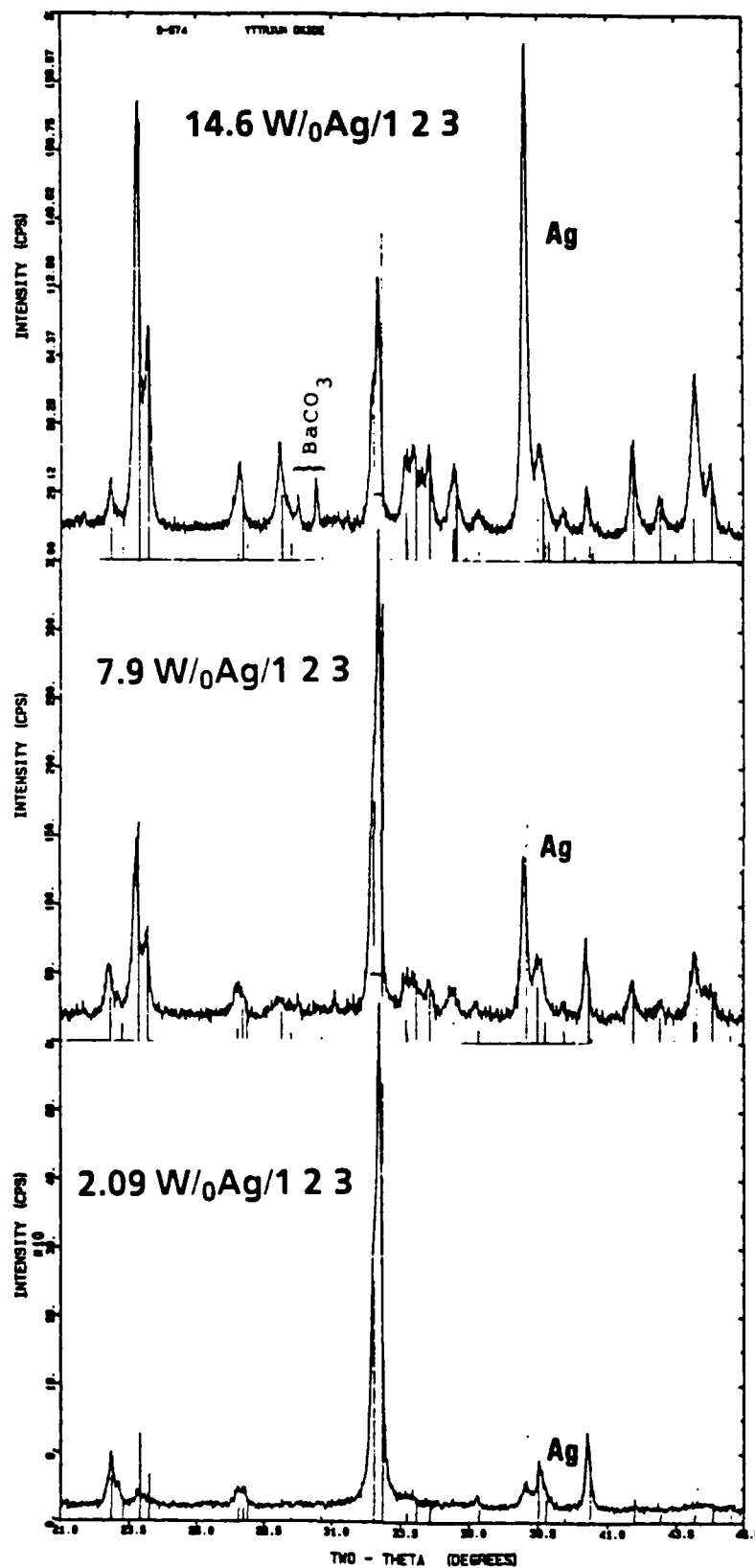
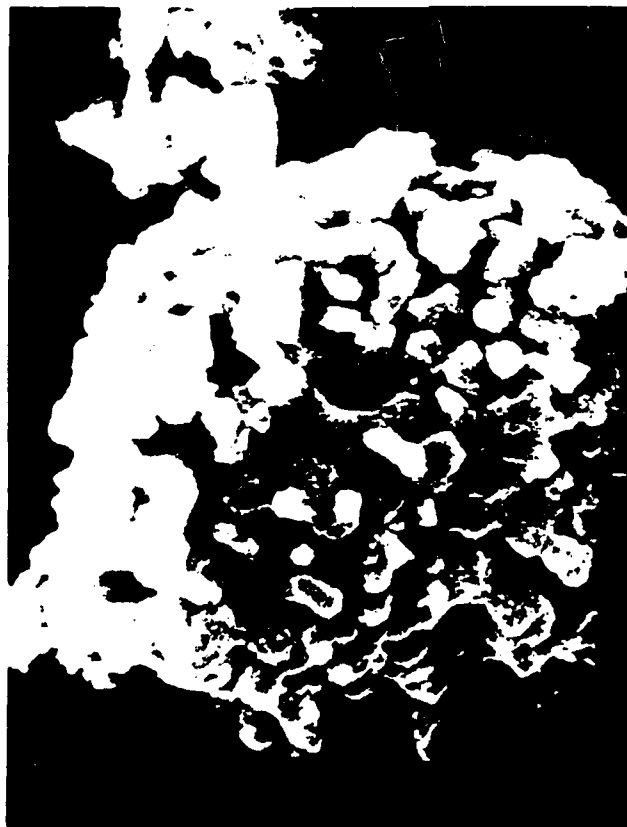


FIGURE 4. POWDER X-RAY SPECTRA OF COATED 123 MATERIAL

AS RECEIVED



Ag COATED



FIGURE 5. SEM PHOTOGRAPHS OF UNCOATED AND COATED 123 POWDER PARTICLES

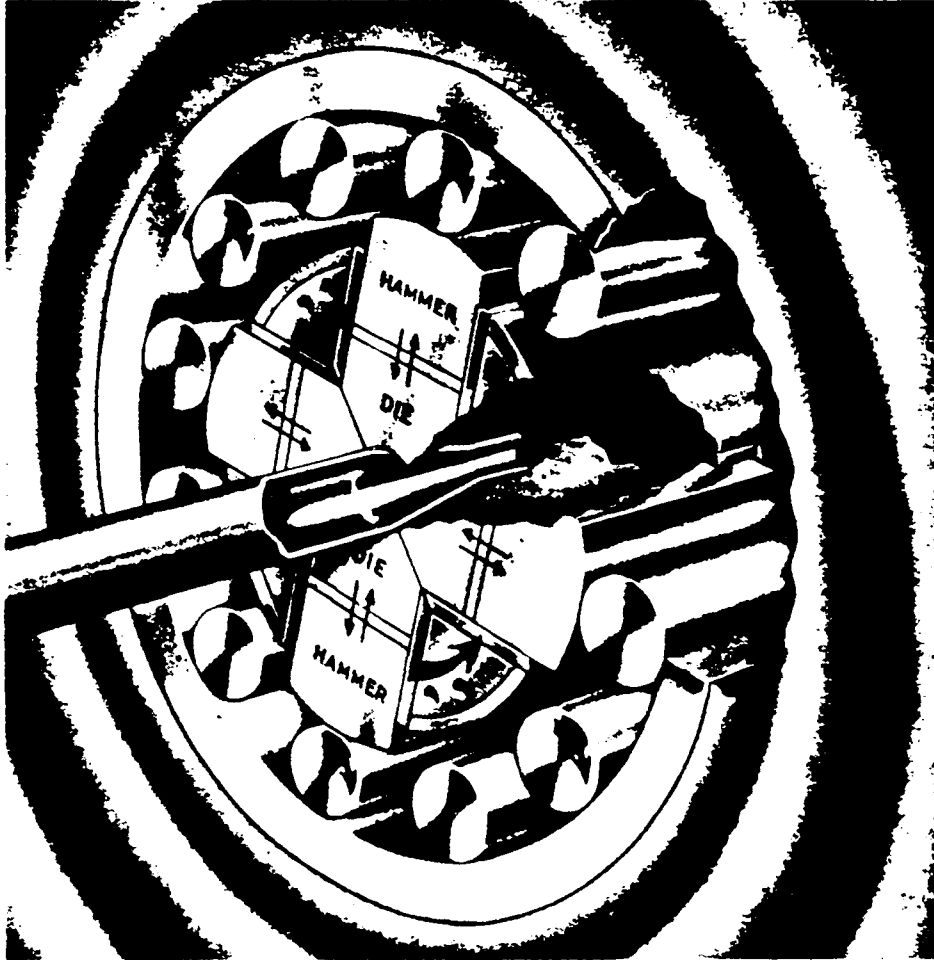


FIGURE 6. SWAGING MACHINE

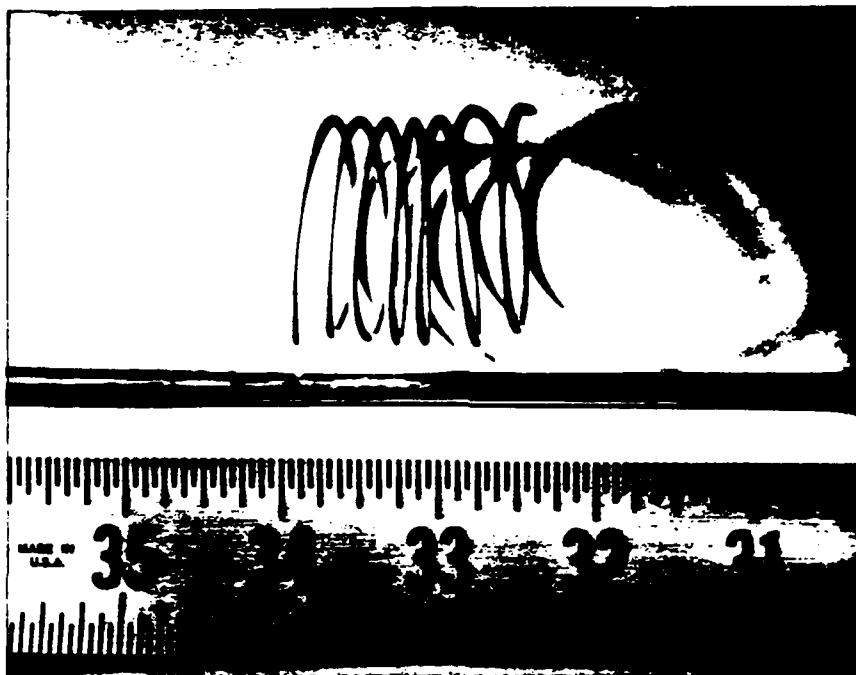


FIGURE 7. HTS POWDER PACKED TUBE AND SWAGED WIRE COIL

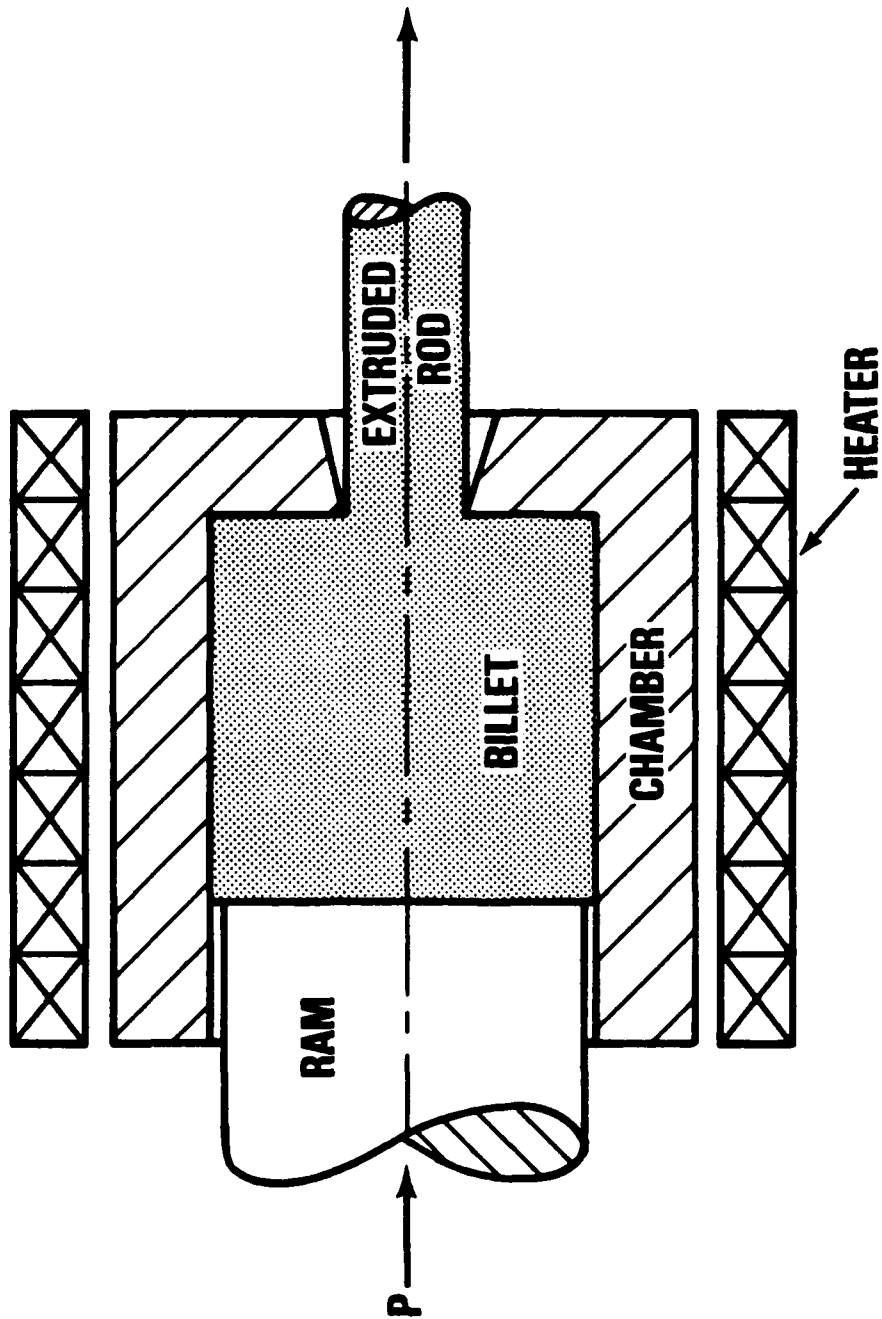


FIGURE 8. EXTRUSION DIE AND BILLET

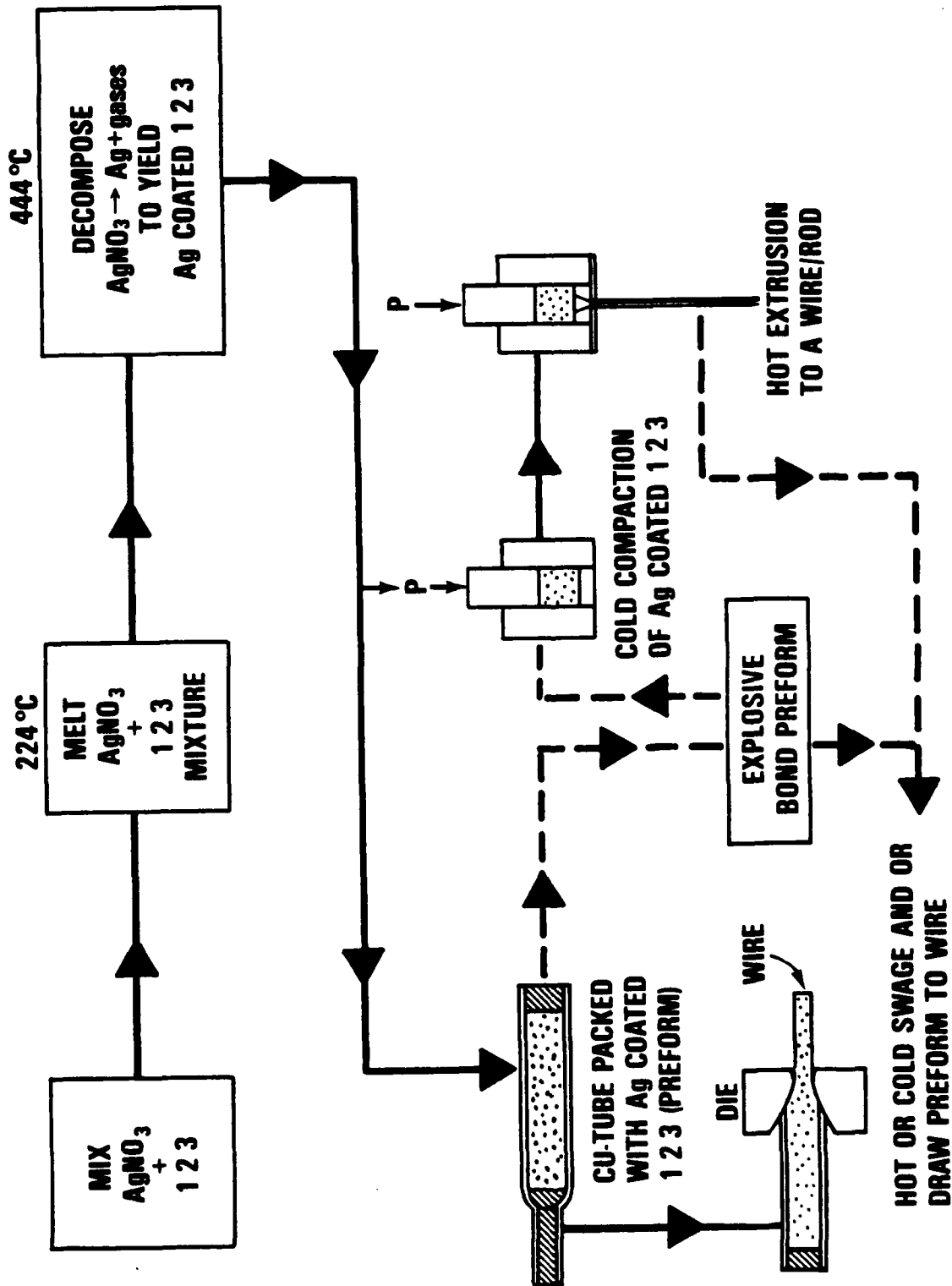


FIGURE 9. HTS WIRE PROCESSING FLOW CHART

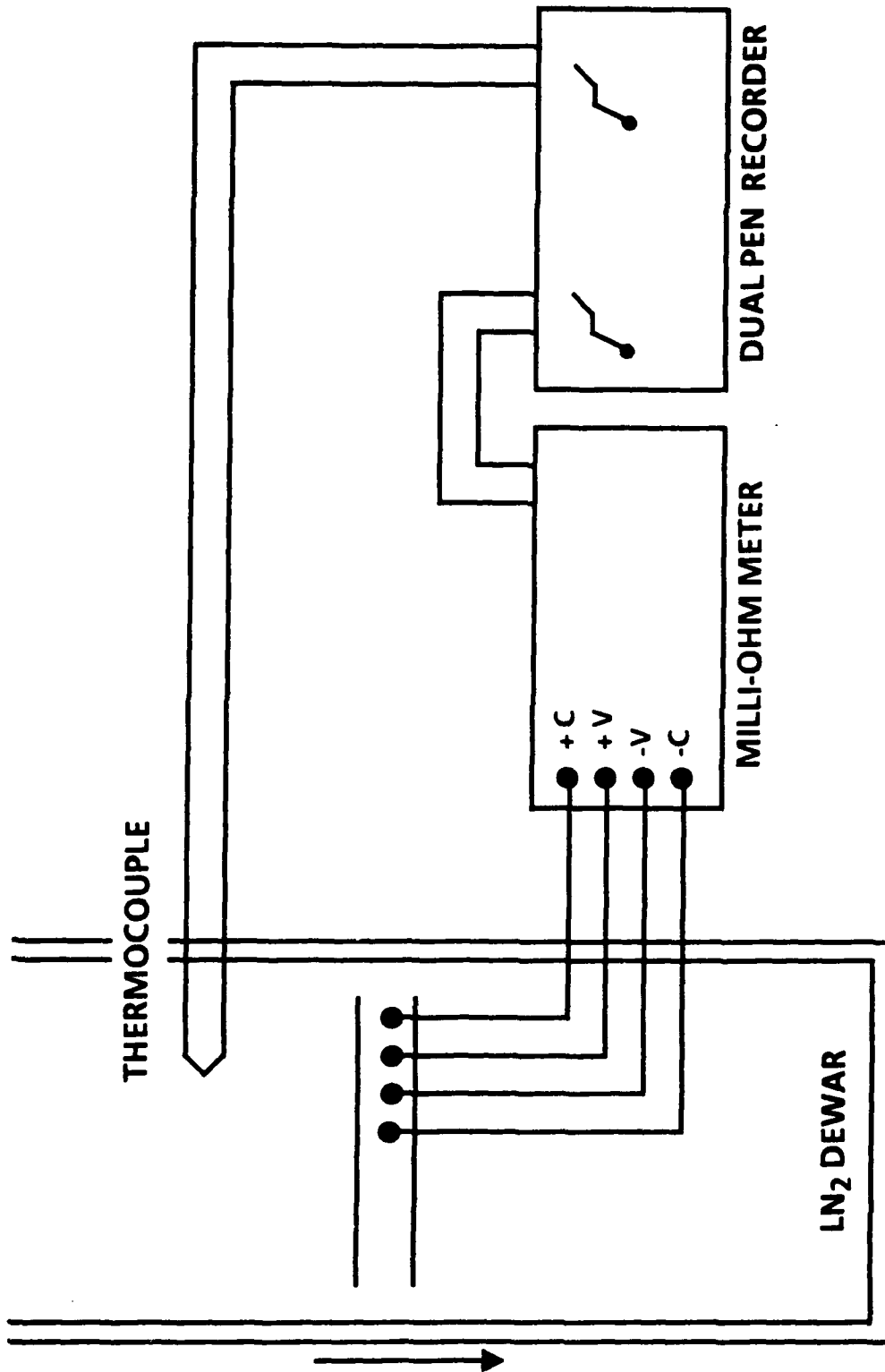


FIGURE 10. APPARATUS FOR T_c MEASUREMENT

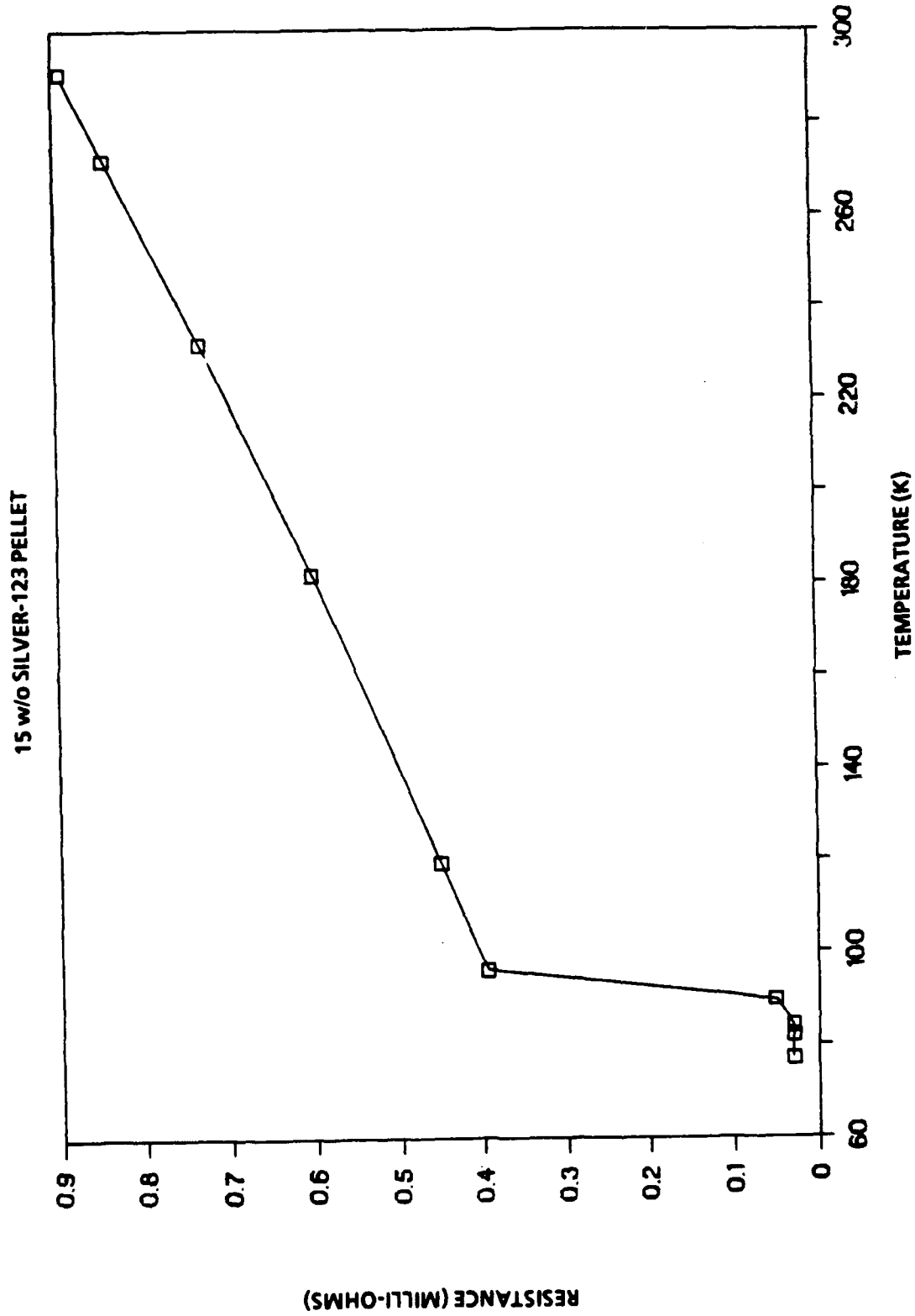


FIGURE 11. RESISTANCE VERSUS TEMPERATURE (K) OF PRESSED PELLET

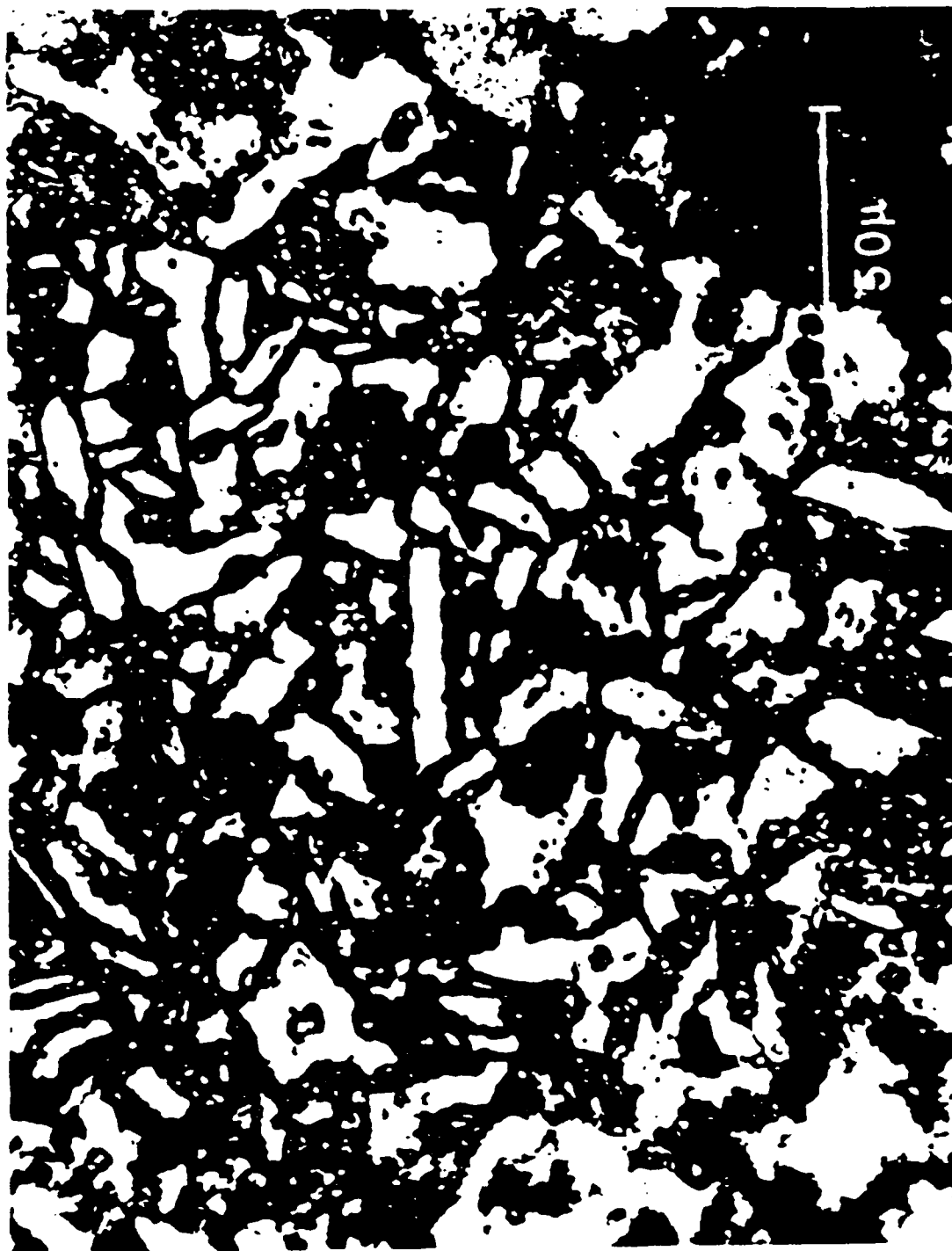


FIGURE 12. MICROSTRUCTURE OF 123 SUPERCONDUCTOR POWDER INFILTRATED
WITH Ag BY AgNO₃ DECOMPOSITION

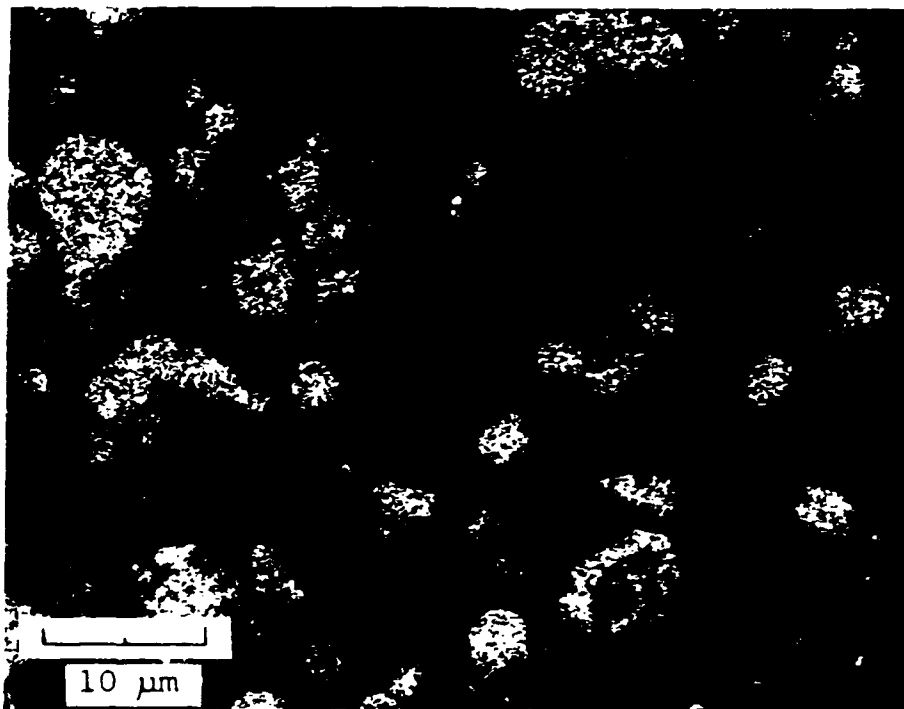
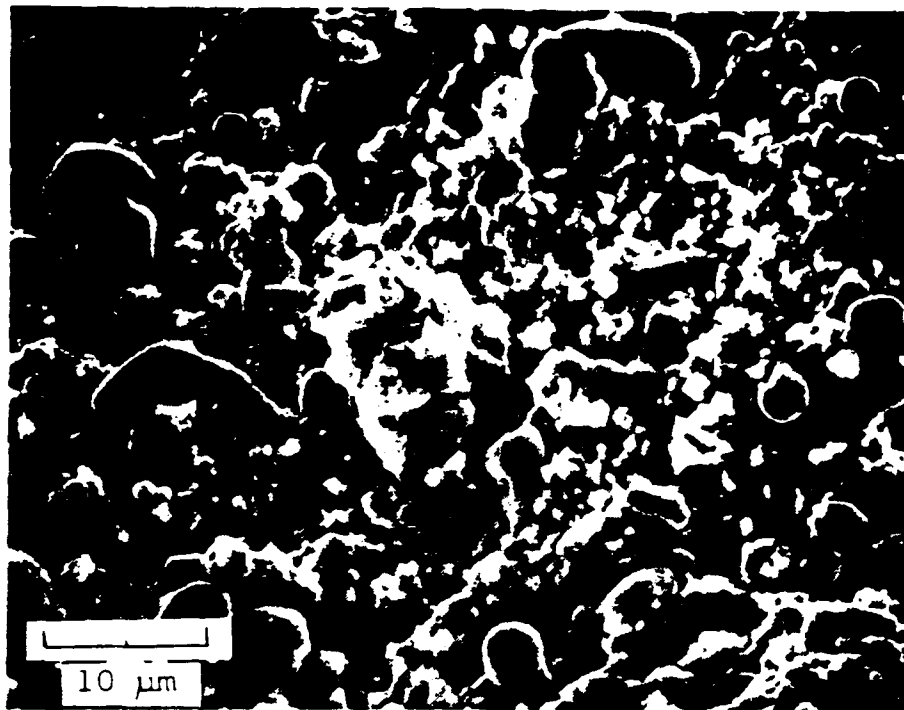


FIGURE 13. Ag/123 ROD CROSS SECTION MICROSTRUCTURE WITH Ag MAP

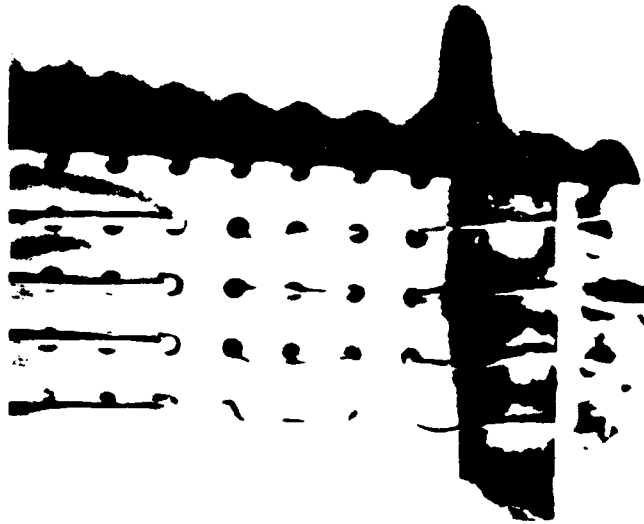
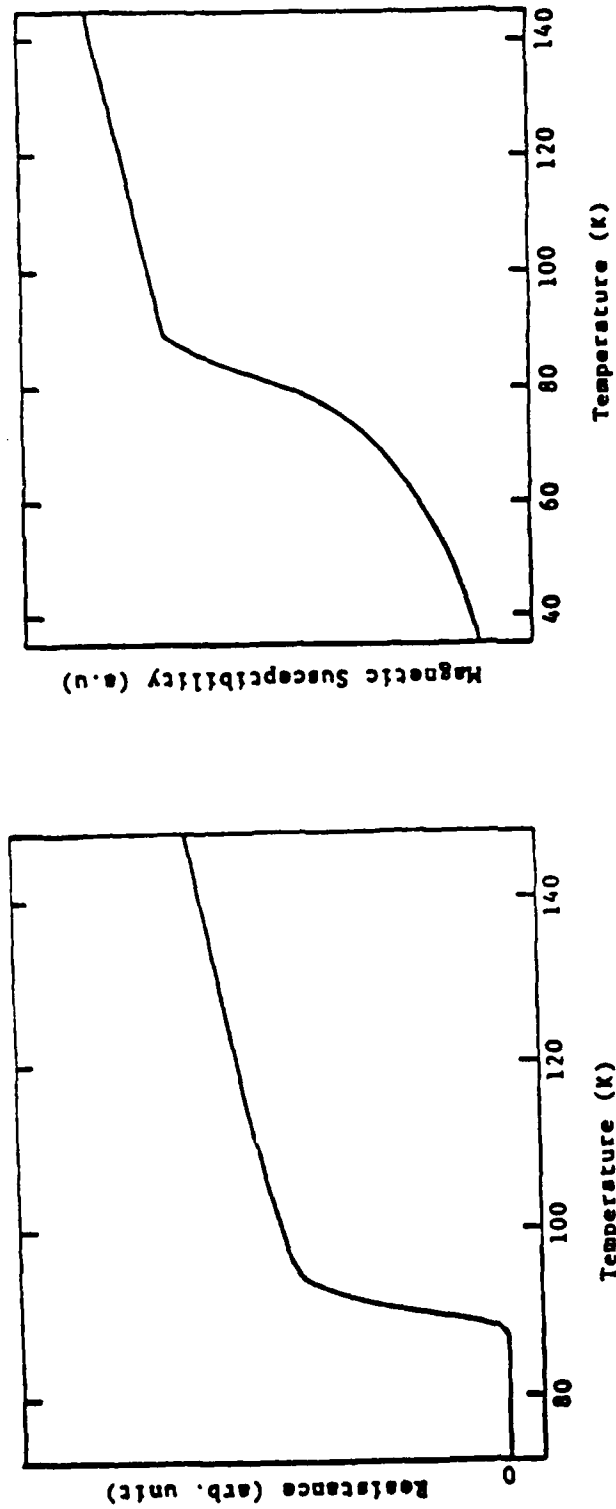


FIGURE 14. SEGMENT OF 123/Ag WIRE IN TEST CONFIGURATION



AC SUSCEPTIBILITY

RESISTANCE MEASUREMENT

FIGURE 15. SUPERCONDUCTING TRANSITION OF SWAGED AND ANNEALED
15wt% Ag/123 ROD

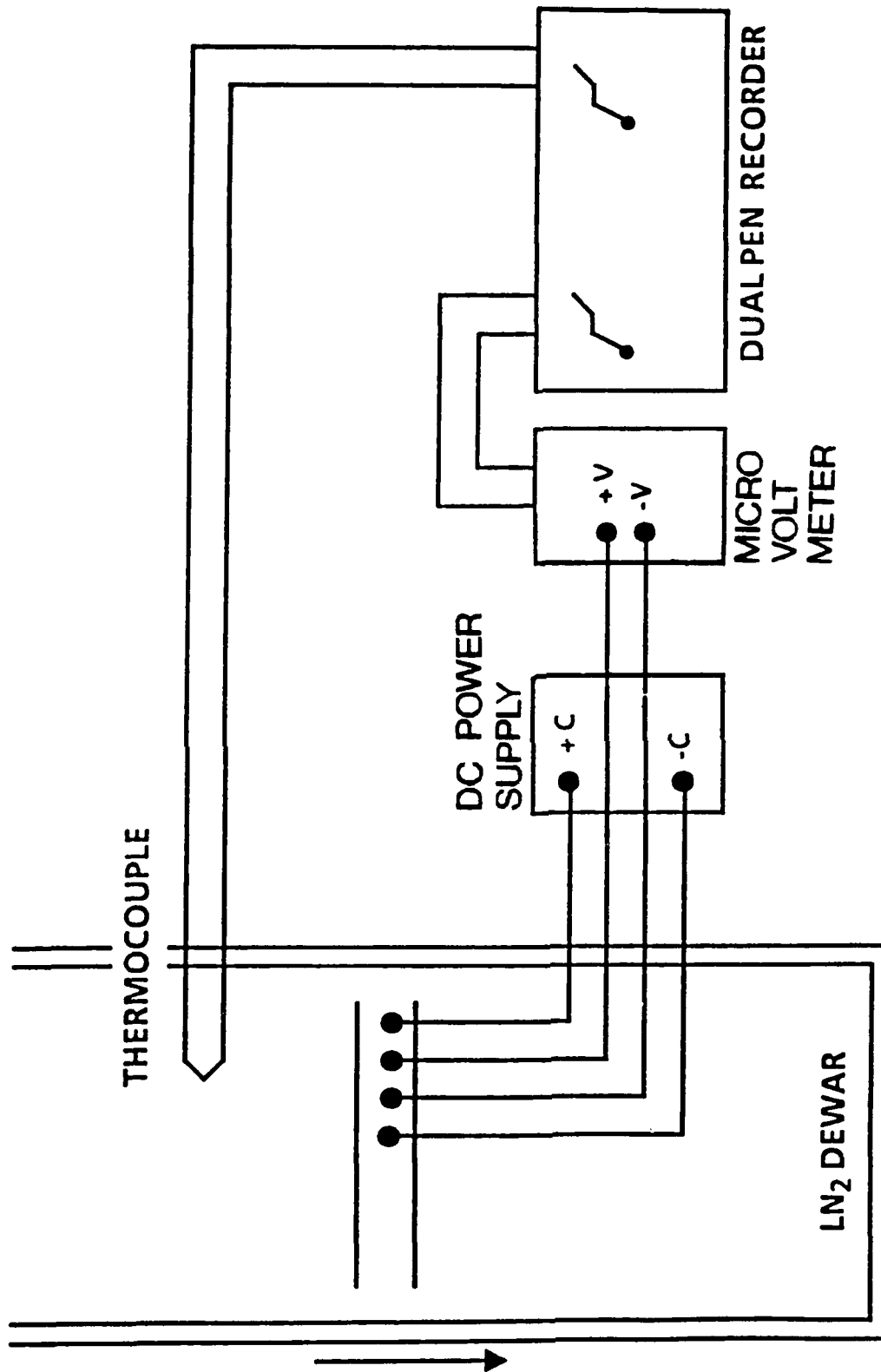


FIGURE 16. DIAGRAM OF J_c MEASUREMENT APPARATUS

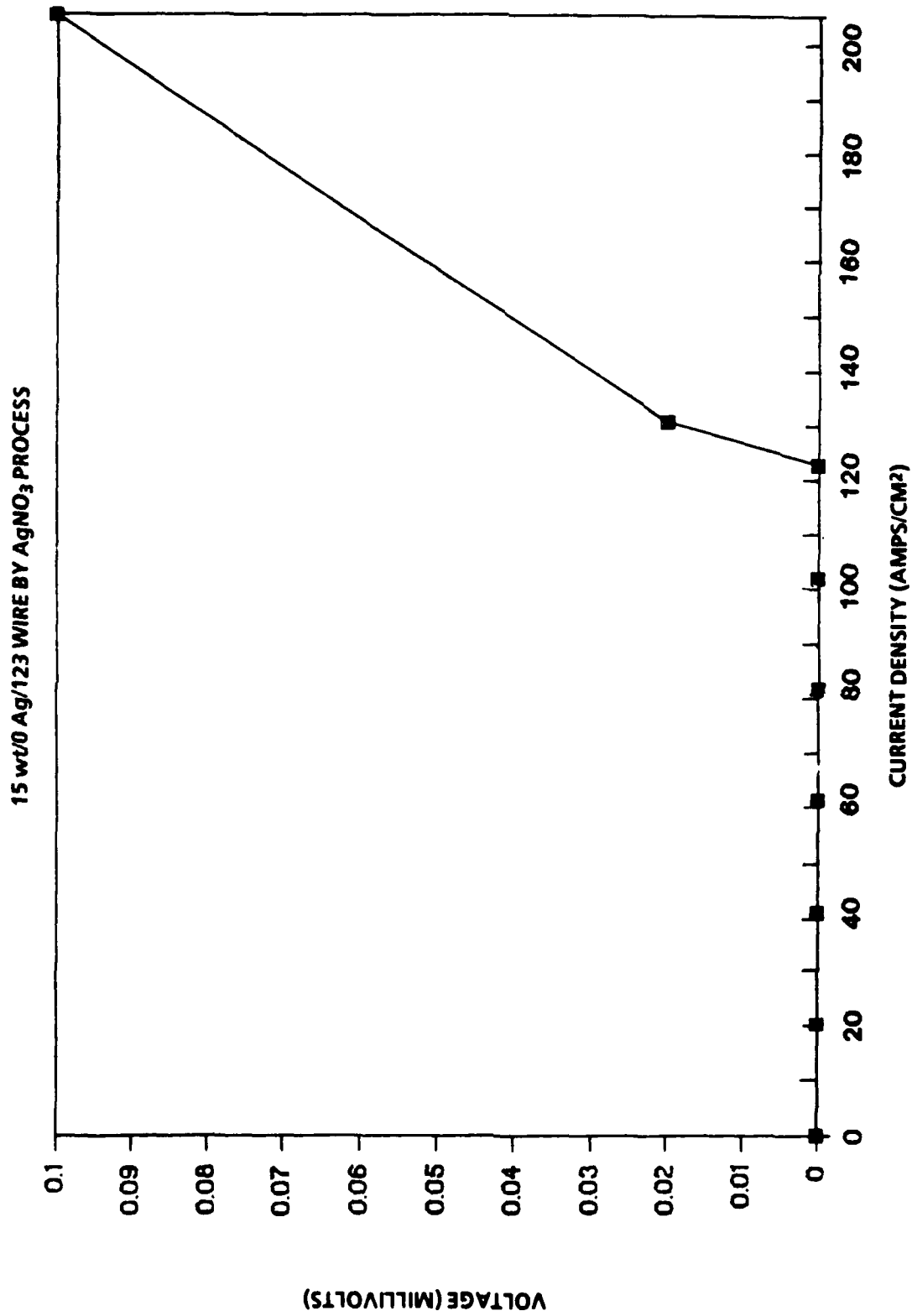


FIGURE 17. CRITICAL CURRENT (J_c) DETERMINATION ON 15 wt% Ag
WIRE SEGMENT AT 77 K

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